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Extended Validation of the Finite Element Model for the 2001 Ford Taurus Passenger Sedan

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ABSTRACT

A finite element (FE) model based on a 2001 Ford Taurus passenger sedan was developed through the process of reverse engineering at the National Crash Analysis Center (NCAC) of The George Washington University (GWU) under an FHWA contract. This model was initially validated by comparing the simulation of the NCAP frontal wall impact with actual data from NHTSA tests for a comparable vehicle. Acceptable results of the initial validation led to the release of the FE model. Subsequently, the model was periodically updated and enhanced with the inclusions of the interior elements. Additional validation efforts were undertaken using data available from other crash tests, including full frontal wall, offset deformable barrier, moving deformable barrier, and offset rigid pole impacts. Simulation results compared well to data from these tests to determine the validity of the enhanced model. Robustness simulations were also undertaken to demonstrate model performance in simulations of centerline pole impacts and full frontal collisions into a Chevrolet Silverado. The model provided viable representations in these large deformation crash events. The capabilities of the model were also checked by damage consistency comparisons for rigid wall, offset deformable barrier, and centerline pole impacts at varying speeds. The simulations executed without error in these runs and the results reflected the expected responses and consistency with varying parameters. This led to the conclusion that the model was robust across various impact scenarios.

Extended Validation of the Finite Element Model for the 2001 Ford Taurus Passenger Sedan

INTRODUCTION

A finite element (FE) model of a 2001 Ford Taurus was developed at the National Crash Analysis Center (NCAC) of The George Washington University (GWU) under contract with the Federal Highway Administration (FHWA) for studying and advancing vehicle and highway safety research. Reverse engineering methods were employed to build a detailed FE model suitable for different crash conditions. This model has been periodically updated and enhanced to include more detail and improve robustness. Details about the modeling and the outcome of the initial validation efforts are documented in "Development and Validation of a Finite Element Model for the 2001 Ford Taurus" NCAC 2008-T-005 [1]. This document describes the additional validation efforts that were undertaken to enhance the Taurus FE model and assess its robustness for various types of impacts. These efforts were conducted by the NCAC in support of the National Highway Traffic Safety Administration (NHTSA) study "Investigate Self and Partner Protection of New Vehicle Designs Using Structural Modeling," TOPR No. 16 under DTFH61-09-D-00001.

MODEL BUILDING AND INITIAL VALIDATION

A 2001 Ford Taurus was disassembled and each part was scanned to define its geometry, measured for thickness, and classified by material type. Material data for the major structural components were obtained through coupon testing. Standard material types were assigned to any parts for which no test data were available. The final vehicle model is shown in Figure 1. Accelerometers in the vehicle model are used to compare simulation data to test data. The locations of the accelerometers used in this study are shown in Figure 2.

The FE model was initially verified to assure that it was a complete and accurate representation of the actual vehicle. The focus of the initial validation was the comparison of the simulation of the NCAP frontal wall impact with actual data from NHTSA Test 3248 for a comparable vehicle [2].

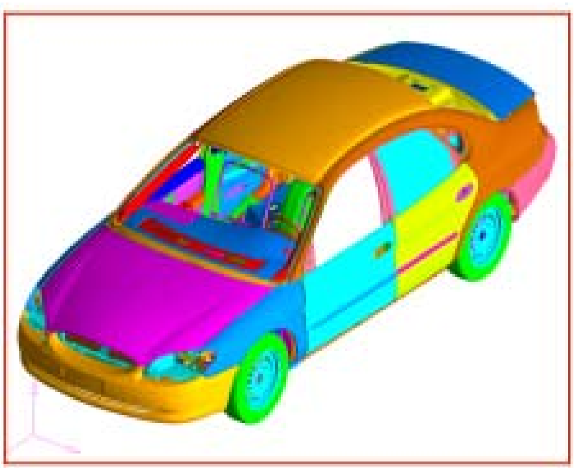

Figure 1 – 2001 Ford Taurus FE model

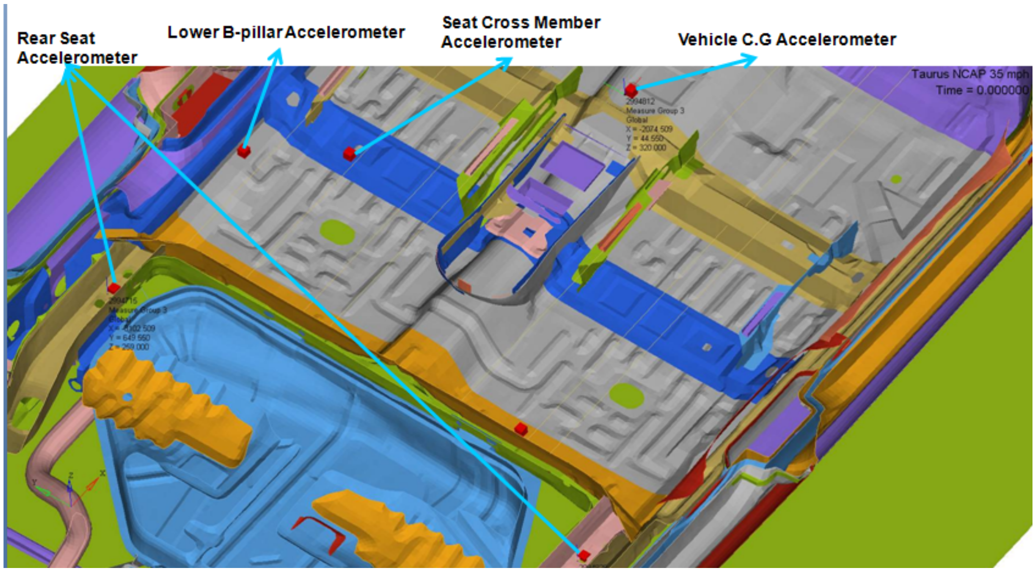

Figure 2 – Accelerometer locations for Ford Taurus FE model

EXTENDED MODEL VALIDATION

The vehicle model was updated to reduce the differences between the test and simulation pulses for full-frontal impacts and rigid pole impacts. In order to improve the correlation between the test and simulation pulses, the material properties were updated, primarily those of the subframe, and the element formulation was changed to fully integrate for some key components. The details of this updated model are shown in Table 1.

Table 1 – Ford Taurus FE model summary

Number of Parts	802	Nodal Rigid Body Connections	1,930
Number of Nodes	921,793	Extra Node Set Connections	53
Number of Shells	838,880	Rigid Body Connections	6
Number of Beams	10	Spotweld Connections	5,557
Number of Solids	134,449	Joint Connections	38
Total Number of Elements	973,351		

The Taurus FE model was validated against additional tests where crash data was available, including rigid wall, offset deformable barrier, moving deformable barrier, and offset rigid pole impacts. These simulations were run to verify that the model would yield similar results as the physical test. The primary validation was done with the NCAP frontal test and no further changes were made to the model as a result of these additional comparisons.

NCAP Rigid Wall Test

The updated and enhanced Ford Taurus FE model was used to simulate an NCAP frontal crash into a rigid barrier at 35 mph, using LS-DYNA. Four full frontal NHTSA tests were available for validation of the Ford Taurus FE model, Tests 3248, 4150, 4776, and 5143 [2,3,4,5].

The overall global deformation pattern of the FE model was very similar to that of the NCAP test, as shown in Figure 3. Figure 4 compares the left and right rear seat cross member accelerations of the test and simulation, also indicating similar vehicle behavior between the test and simulation. The Roadside

Safety Verification and Validation Program (RSVVP) was used to generate an objective measure of how well the simulation follows the test data [6]. The Sprague-Geers MPC metrics were used to quantify the similarity of the test and simulation curve shapes and the ANOVA metric was used to evaluate the residual error. The acceptance criteria for the Sprague-Geers metrics are a difference of less than 40% in magnitude, phase, or comprehensive (the square root of the sum of the squares of M and P). The acceptance criteria for the ANOVA metric are an average residual error of less than 5% and a standard deviation of the residual errors of less than 20%. When the values fall under these acceptance criteria, the simulation can be said to have good correlation with the test, with any deviations in the data attributable to random experimental error. These objective rating metrics for the left and right rear seat accelerations compared to Test 4776 are summarized in Table 2. It is worth noting that the acceptance criteria in RSVVP were developed for roadside safety applications where the tests typically involve longer duration complex impact sequences with more variability than the NHTSA vehicle crash tests being considered for the FE model validation. In the future, developing acceptance criteria for NHTSA type crash tests would be more pertinent and applicable to vehicle FE model validation efforts.

Figure 3 – Comparison of the global deformation for Taurus in NCAP test and simulation

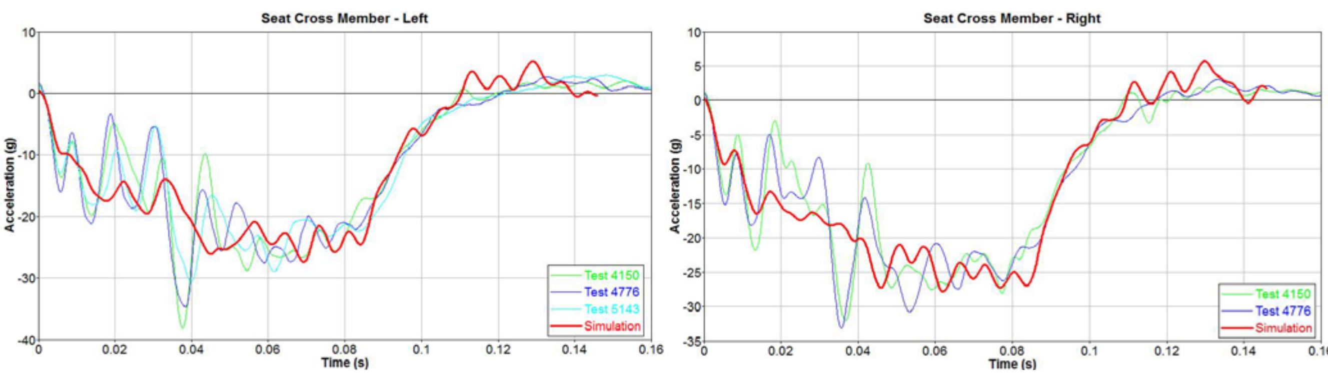

Figure 4 – Comparison of left and right rear seat cross member X accelerations for tests and simulation

Table 2 – Objective rating criteria for left and right rear seat cross member accelerations

		Left Rear Seat Acceleration		**Right Rear Seat Acceleration**	
		Value (%)	Pass?	Value (%)	Pass?
Sprague-Geers MPC Metric	Magnitude	0.4	Y	0.6	Y
	Phase	7.7	Y	7.7	Y
	Comprehensive	7.7	Y	7.7	Y
ANOVA Metric	Average	0.4	Y	0.3	Y
	Standard Deviation	11.8	Y	12.4	Y

Lastly, the simulation and test forces were compared (Figure 5). The total wall force in the simulation closely matched that of the two tests. The similarity of the simulation and Test 4776 wall force curves is quantified in Table 3. Additionally, similar stiffness was observed in the FE model and test vehicles, as shown in the force-displacement plot.

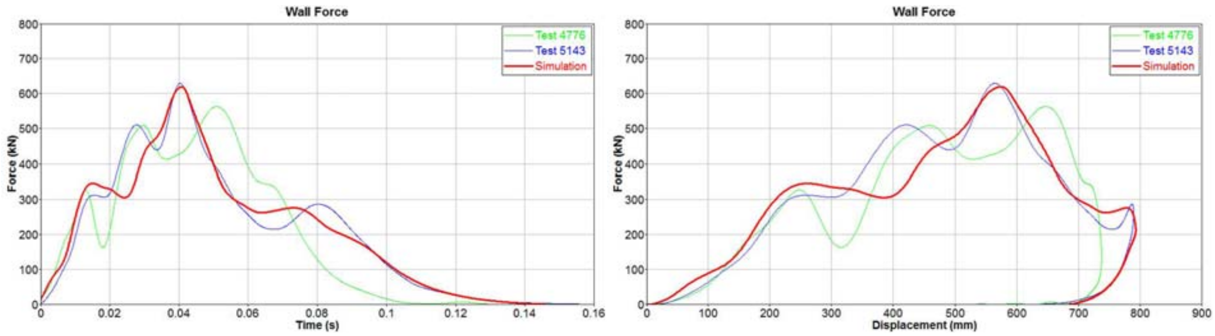

Figure 5 – Total wall force (left) and force-displacement (right) plots for the tests versus simulation

Table 3 – Objective rating criteria for total wall force

		Total Wall Force	
		Value (%)	Pass?
Sprague-Geers MPC Metric	Magnitude	-1.5	Y
	Phase	4.7	Y
	Comprehensive	4.9	Y
ANOVA Metric	Average	-0.1	Y
	Standard Deviation	6.4	Y

Matching the vehicle pulse was the most important factor in this validation. However, intrusion data was available, so these were compared as well. The intrusion measurements showed a good match between Test 4150 and the simulation on both the driver and passenger sides (Table 4 and Table 5).

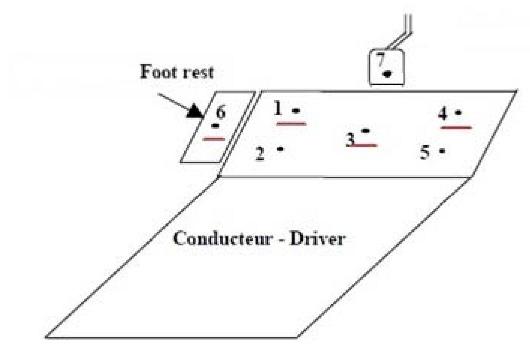

Figure 6 – Diagram of the intrusion measurement points for the driver side floor pan

Table 4 – Driver side intrusion

Item	Test 4150 (mm)	V 4d
1	-111	-117
3	-115	-123
4	-136	-158
6	-72	-66

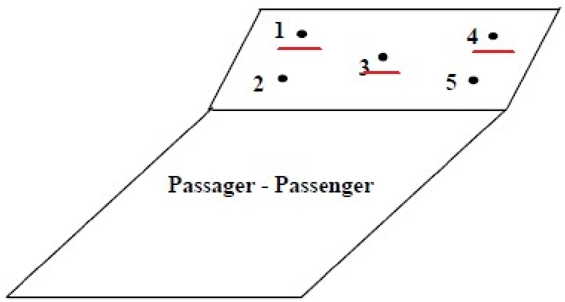

Figure 7 – Diagram of the intrusion measurements points for the passenger side floor pan

Table 5 – Passenger side intrusion

Item	Test 4150 (mm)	V4d
1	-143	-145
3	-122	-115
4	-123	-131

All of the data presented above validates the FE model of the Ford Taurus as a good representation of the physical vehicle.

Full Frontal Impact at 30 mph

The model was also verified against a full frontal impact into a rigid wall at 30 mph (NHTSA Tests 3150, 3224, 4134, 4135, and 4174) [7, 8, 9, 10, 11]. The overall global deformation pattern of the FE model was very similar to that of the NHTSA test, as shown in Figure 8. Figure 9 compares the left and right rear seat cross member accelerations of the test and simulation, also indicating similar vehicle behavior between the test and simulation (Table 6).

Figure 8 – Comparison of the global deformation for Taurus in 30 mph frontal test and simulation

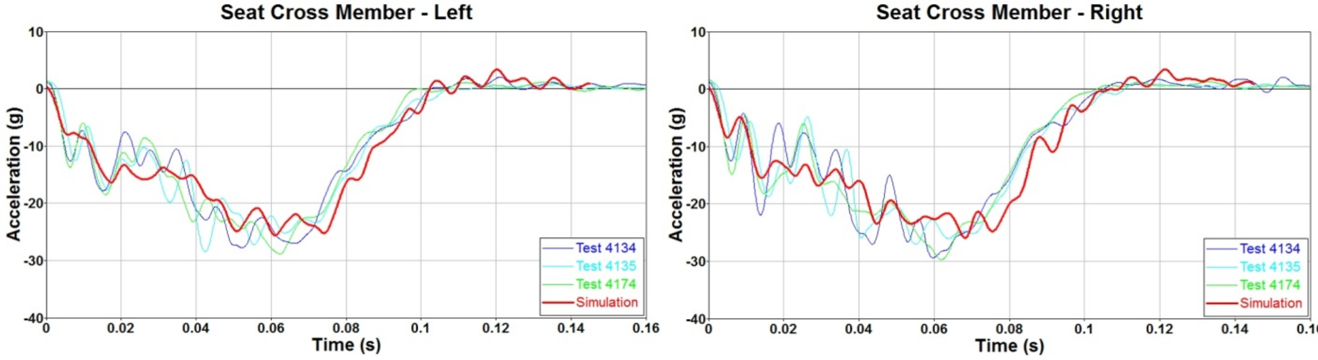

Figure 9 – Comparison of left and right rear seat cross member X accelerations for 30 mph tests and simulation

Table 6 – Objective rating criteria for left and right rear seat accelerations for 30 mph full frontal impact

		Left Rear Seat Acceleration		Right Rear Seat Acceleration	
		Value (%)	Pass?	Value (%)	Pass?
Sprague-Geers MPC Metric	Magnitude	-1	Y	-2.1	Y
	Phase	6.3	Y	7.2	Y
	Comprehensive	6.3	Y	7.5	Y
ANOVA Metric	Average	0.2	Y	0.5	Y
	Standard Deviation	9.6	Y	11.9	Y

All of the data presented above further verified that the FE model of the Ford Taurus is a good representation of the physical vehicle.

IIHS Offset Deformable Barrier

The model was run under the IIHS offset deformable barrier (ODB) crash test protocol, in which the vehicle strikes a deformable barrier at 40 mph with a 40% overlap on the driver side. The simulation results were compared to IIHS Test CF00010 [12]. The overall vehicle deformation and pulse were similar between the test and simulation (Figure 10 and Figure 11). Table 7 summarizes the objective rating criteria for the simulation data compared to the test data.

Figure 10 – Comparison of post-impact deformation of IIHS ODB test

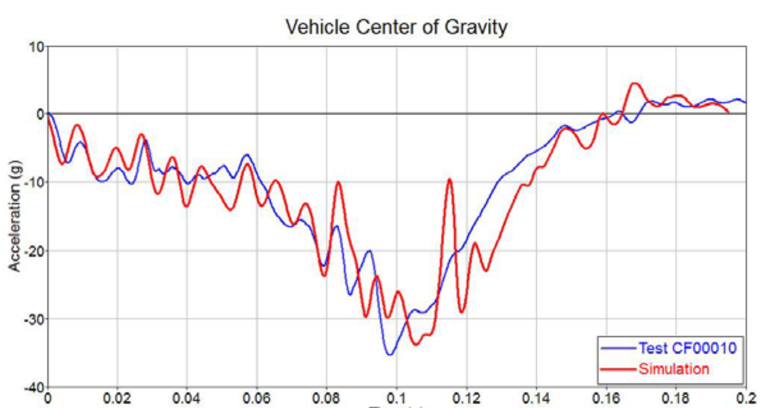

Figure 11 – Acceleration at the vehicle CG for the IIHS ODB test and simulation

Table 7 – Objective rating criteria for vehicle CG acceleration in the IIHS ODB simulation

		CG Acceleration	
		Value (%)	Pass?
Sprague-Geers MPC Metric	Magnitude	3.2	Y
	Phase	8.6	Y
	Comprehensive	9.2	Y
ANOVA Metric	Average	-1.2	Y
	Standard Deviation	10.8	Y

The intrusion was also compared between the test and simulation (Figure 12). A quantitative comparison of the intrusion at four measurement points in the footwell area is shown in Table 8.

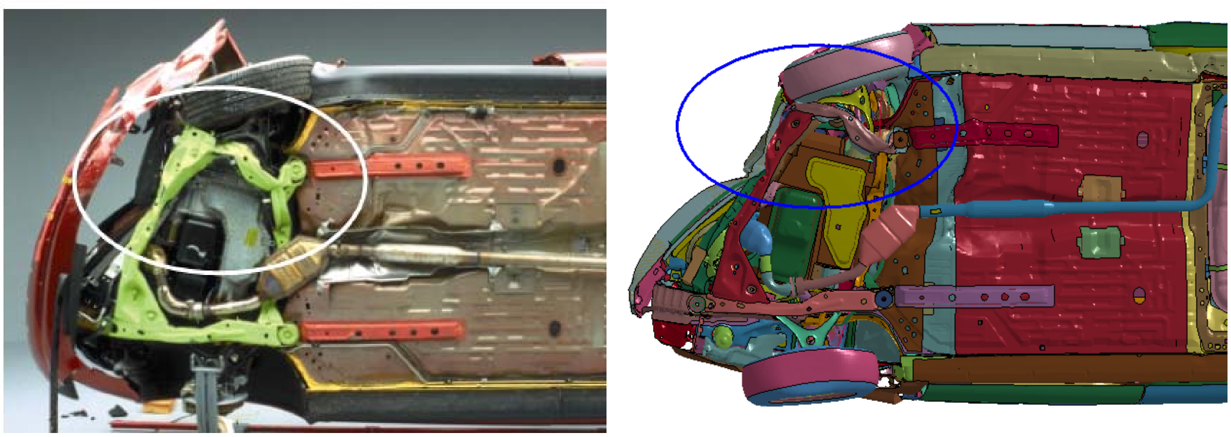

Figure 12 – Post-crash footwell intrusion comparison

Table 8 – Comparison of footwell intrusion between IIHS test and simulation

Location	IIHS test(mm)	Simulation(mm)
Footrest	-70	-105
Left toepan	-110	-166
Center toepan	-120	-161
Right toepan	-120	-156

MDB Side Impact

The Ford Taurus model was run in a side impact with a moving deformable barrier (MDB). The MDB had an initial velocity of 38.2 mph and was crabbed at a 27° angle. The Taurus was stationary and positioned at a 63° angle from the MDB's axis of forward motion. The simulation set up is illustrated in Figure 13.

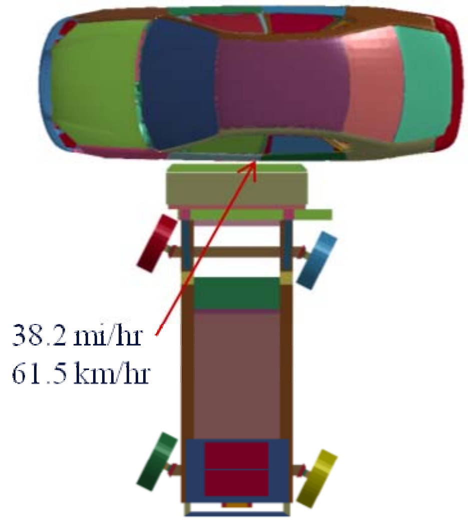

Figure 13 – Diagram of the MDB side impact test set up

The simulation results were compared to data from NHTSA Test 3263 [13]. The post-crash deformation profiles and vehicle accelerations show reasonable correlation (Figure 14, Figure 15, and Figure 16).

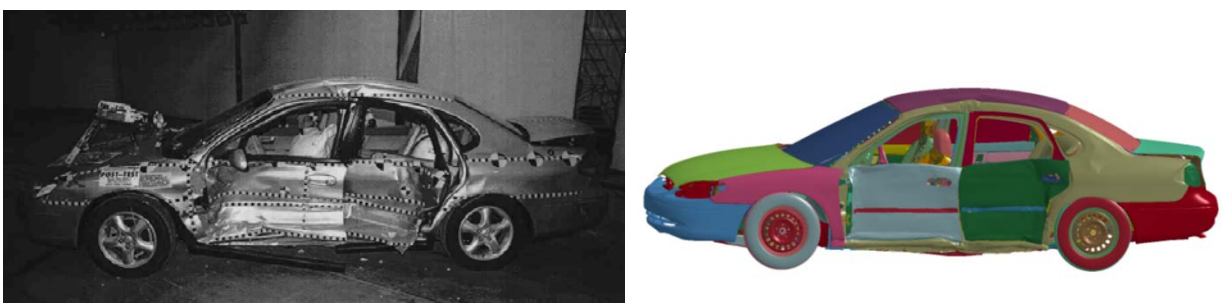

Figure 14 – Post-crash deformation of Taurus in side impact

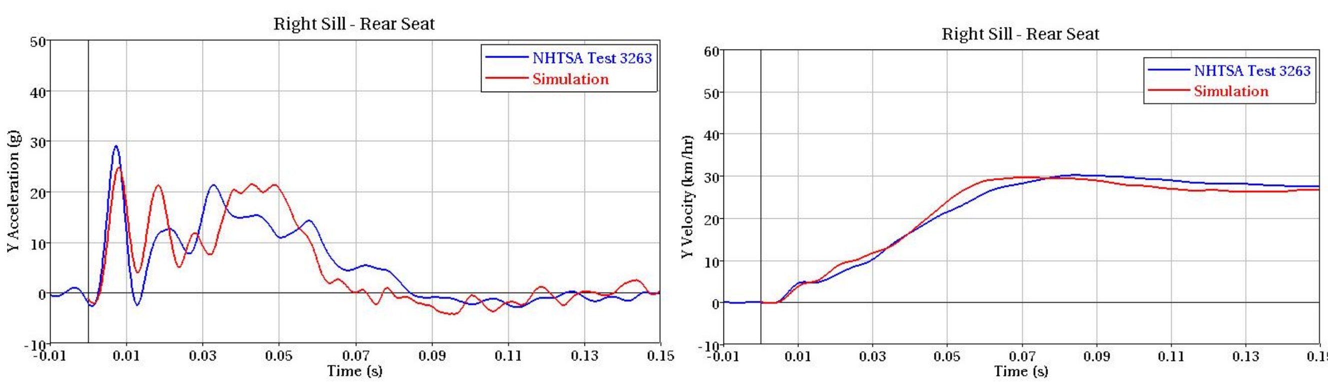

Figure 15 – Overall acceleration and velocity of the vehicle as captured by the right rear seat accelerometer

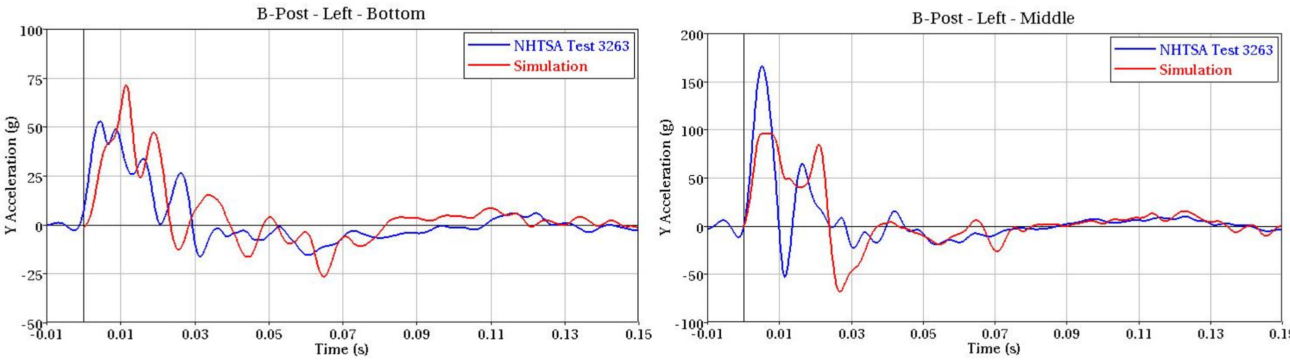

Figure 16 – Intrusion acceleration as measured at the bottom and middle of the struck side B-pillar

The intrusion was measured at three levels—sill top, occupant h-point, and window sill—in order to quantify the deformation profile and compare the test and simulation (Figure 17). The measurements showed acceptable correlation between the test and simulation. The difference in the rear section of the vehicle is associated with the fact that the rear door bent during the impact, which did not occur in the simulation because the door lock was modeled as a rigid connection.

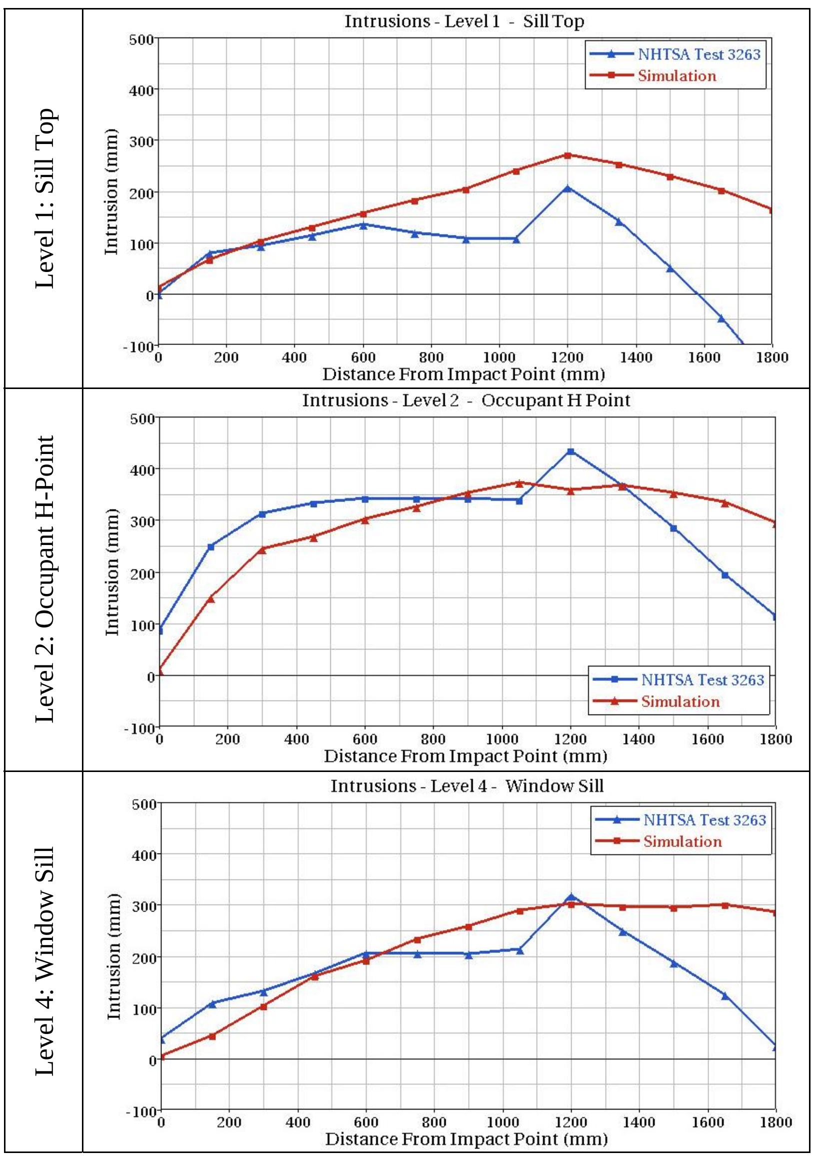

Figure 17 – Intrusion measured at three levels after side impact

Offset Rigid Pole at 35 mph

The Taurus FE model was run in an offset impact with a rigid 10” pole at 35 mph. The pole was offset 15% (27.7 cm) to the left of the vehicle centerline. Post-impact pictures and vehicle motion are shown in Figure 18 and Figure 19 for IIHS Test CF05001 and the simulation [14]. Due to the fact that failure was not incorporated in the model, specifically for the engine mounts, the simulation results do not capture the response seen in the tests.

Figure 18 – Post-crash images of the Taurus in an offset rigid pole impact

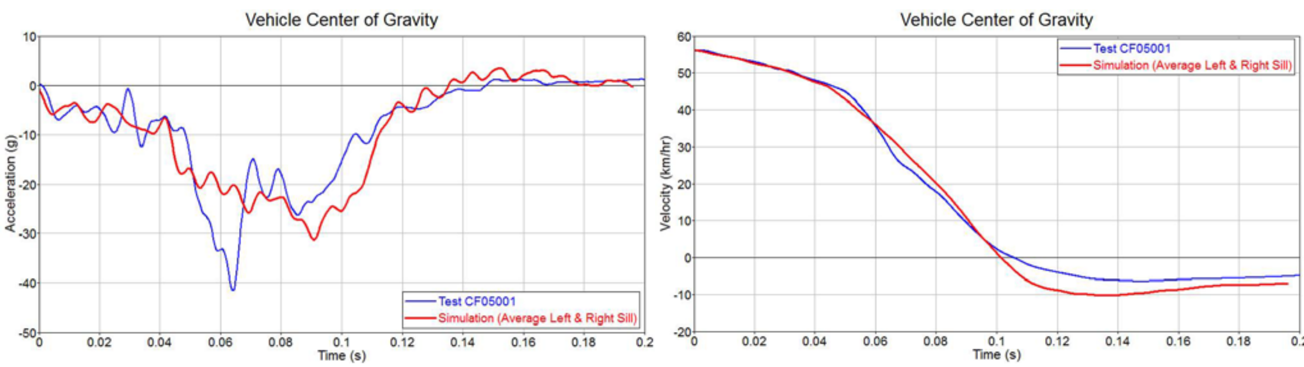

Figure 19 – Taurus acceleration and velocity measured at the vehicle CG

Offset Rigid Pole at 40 mph

The Taurus FE model was run in an offset impact with a rigid 10” pole at 40 mph. The pole was offset 16% (30.5 cm) to the left of the vehicle centerline. Post-impact pictures and vehicle motion are shown in Figure 20 and Figure 21 for the IIHS Test CF05002 and the simulation [15].

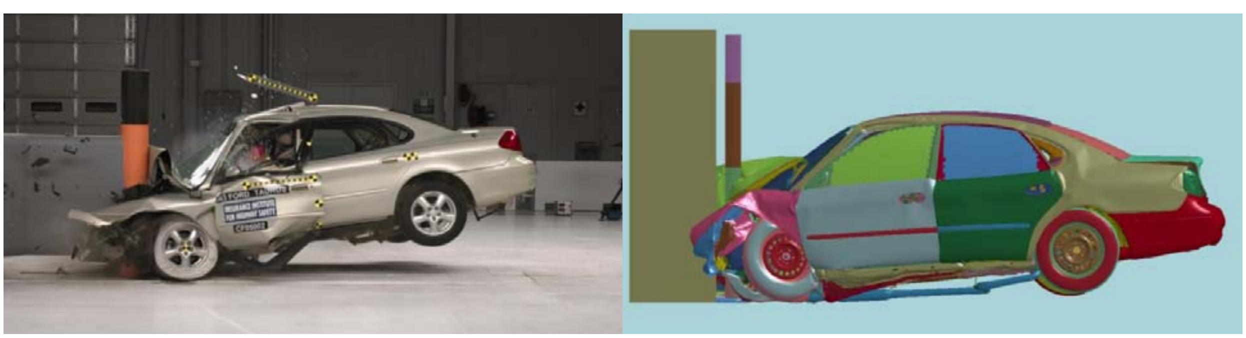

Figure 20 – Post-crash images of the Taurus in an offset rigid pole impact

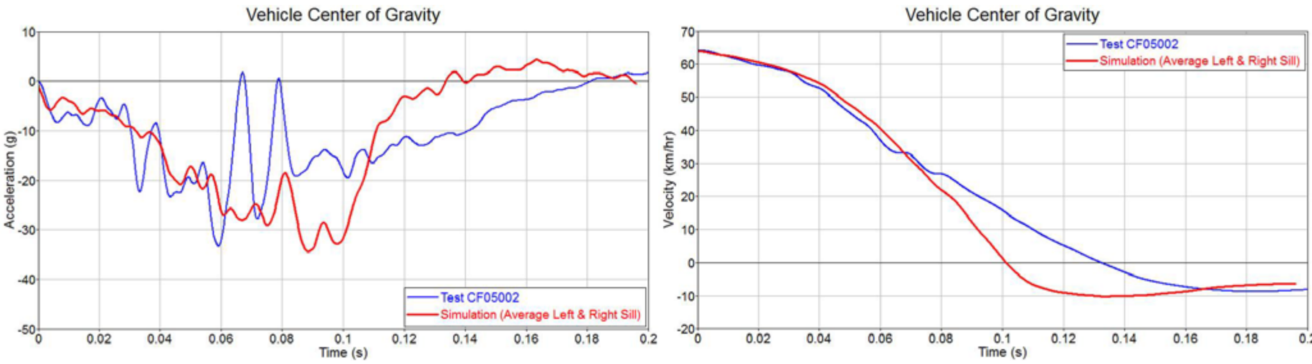

Figure 21 – Taurus acceleration and velocity measured at the vehicle CG

MODEL ROBUSTNESS

The FE model of the Ford Taurus was run in several different crash configurations to confirm that the simulations would run to completion with no computational errors. The centerline pole impact at 35 mph was selected for one of the robustness runs, as it is a severe, high speed crash with large, localized deformation. This crash condition would test the robustness of the FE model. Additionally, the Taurus model was tested for robustness in full frontal and 40% offset impacts with the 2007 Chevrolet Silverado FE model.

Centerline Pole at 35 mph

The centerline pole simulation was run with the Ford Taurus at an impact speed of 35 mph. The model was proven to be robust, as no errors were encountered and the simulation ran to completion. The pre- and post-crash images showing the severity of the deformation is shown in Figure 22 and the vehicle acceleration is shown in Figure 23.

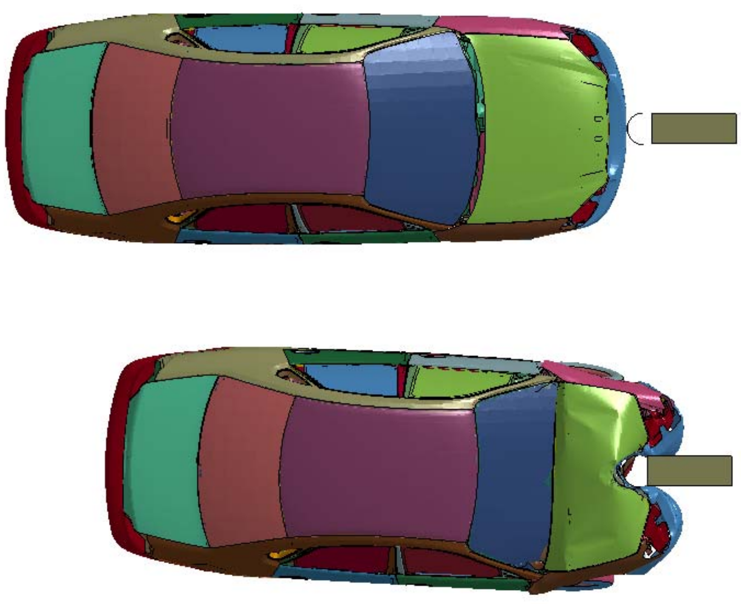

Figure 22 – Pre- and post-crash images of the Taurus for the centerline pole robustness simulation

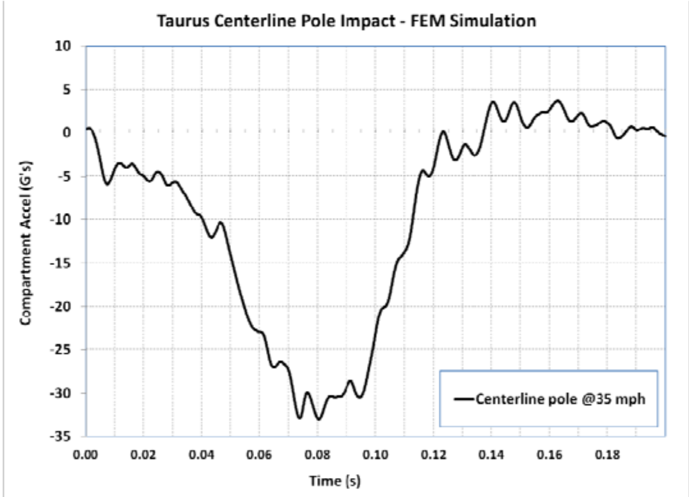

Figure 23 – Compartment acceleration of Taurus in centerline pole impact at 35 mph

Full Frontal Impact into Silverado

The Taurus was run into the Chevy Silverado pick-up truck in a full frontal impact at 35 mph. This simulation ran to completion with no errors. The extent of the deformation is shown in Figure 24 and the vehicle pulse is shown in Figure 25. The accelerations for the right rear seat and left rear seat are similar, showing a symmetrical impact as expected of a full frontal crash.

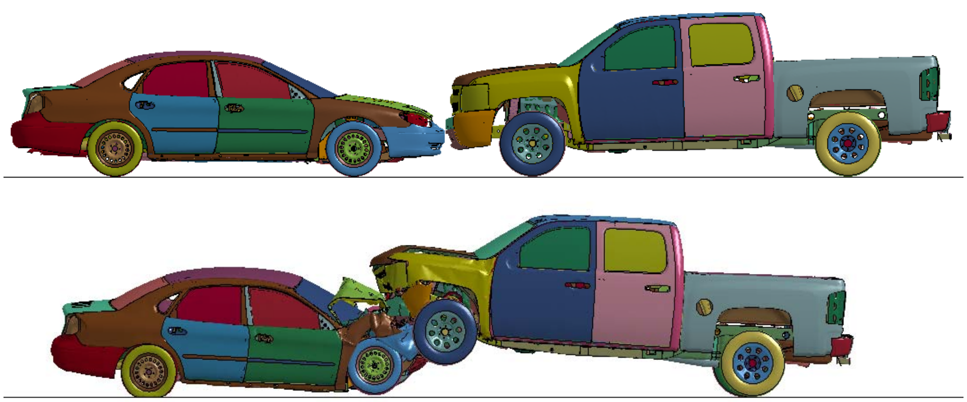

Figure 24 – Pre- and post-crash images of the Taurus striking the Silverado with 100% overlap

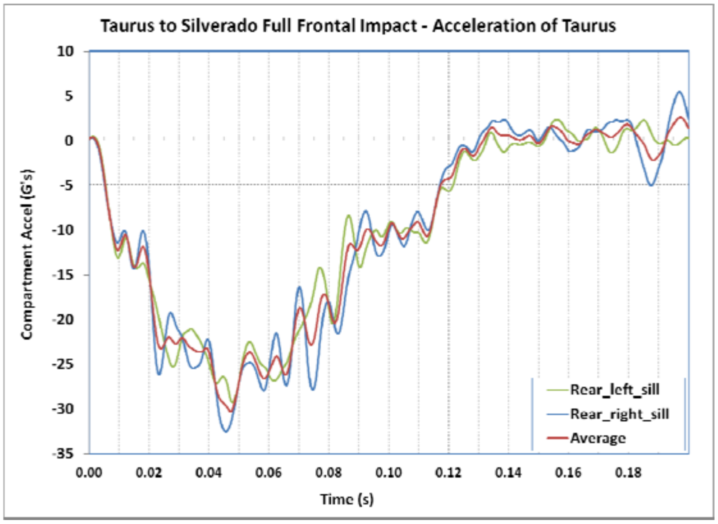

Figure 25 – Compartment acceleration of Taurus in full frontal impact with Silverado

Offset Impact into Silverado

The Taurus model was run into the Silverado model at 35 mph with a 40% overlap. This simulation ran to completion with no errors, showing the robustness of the Taurus FE model. The deformation of the Taurus is shown in Figure 26 and the vehicle pulse is shown in Figure 27. The acceleration of the left rear seat was greater than that of the right rear seat, as expected in an offset crash on the driver side of the vehicle.

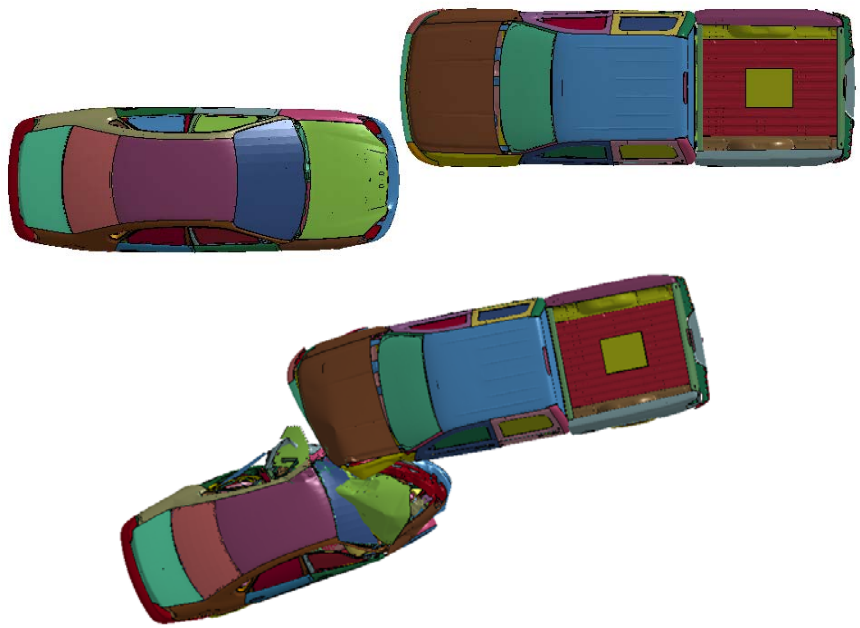

Figure 26 – Pre- and post-crash images of the Taurus striking the Silverado with 40% overlap

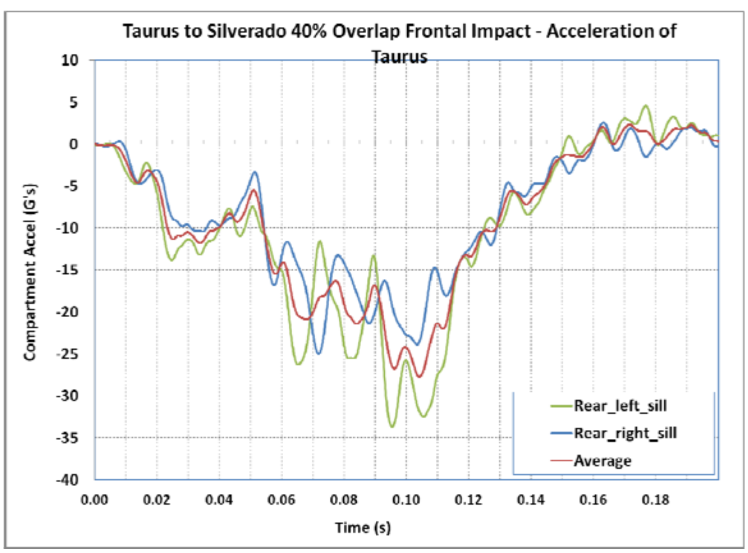

Figure 27 – Compartment acceleration of Taurus in 40% offset impact with Silverado

VARYING SPEED TREND ANALYSIS

Several more simulations were run with the Ford Taurus FE model to verify that the model was showing the expected trends in different crash configurations. The NCAP rigid wall, IIHS offset deformable barrier, and centerline pole simulations were run and the results were compared between low and high speeds within the same crash configuration to confirm that the vehicle responses were valid in the physical realm.

NCAP Rigid Wall

The NCAP rigid wall simulation was run at 25 mph and 35 mph. The pre- and post-crash images and resulting compartment accelerations are shown in Figure 28 and Figure 29. These runs verified that the higher speed impact yielded a more severe crash pulse than the lower speed impact.

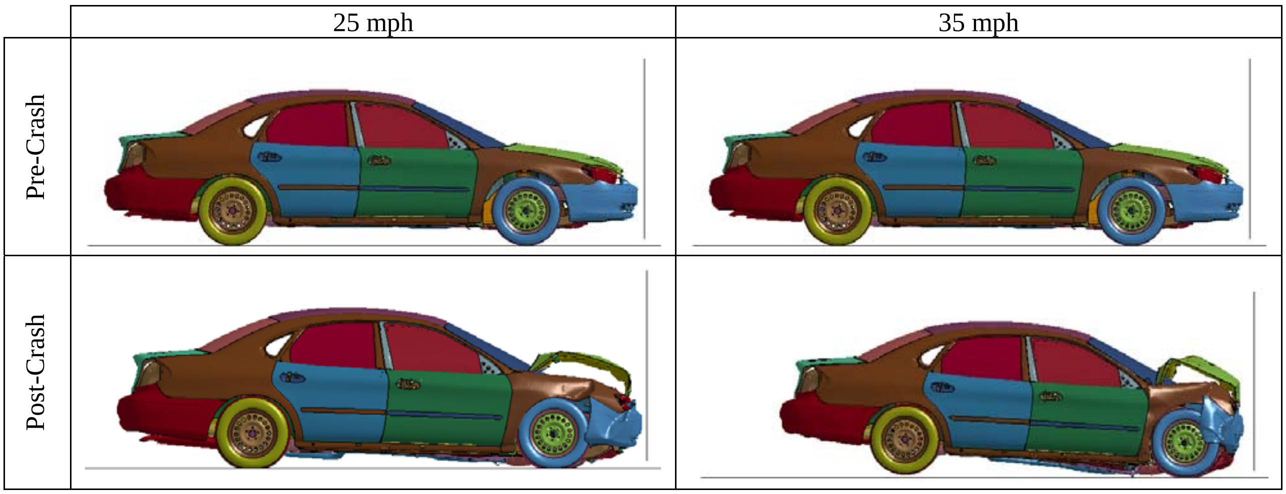

Figure 28 – Pre- and post-crash images of the Taurus for the full frontal impact at 25 mph and 35 mph

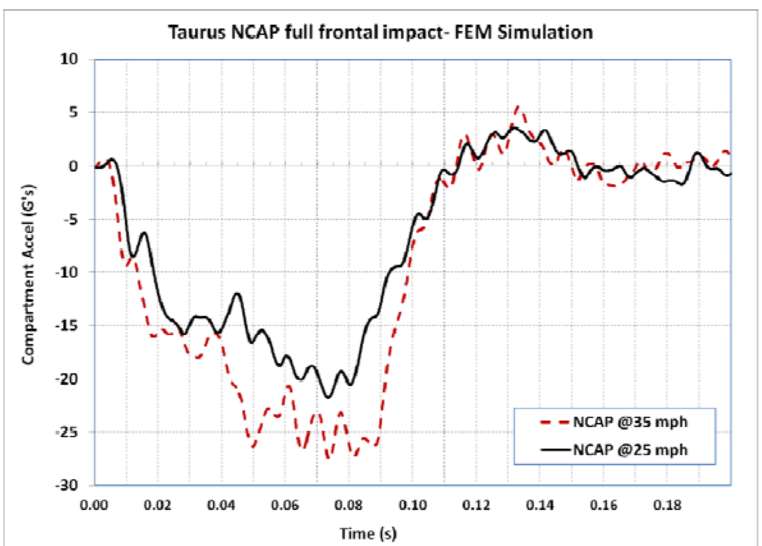

Figure 29 – Taurus compartment accelerations for NCAP frontal verification simulations

IIHS Offset Deformable Barrier

The IIHS ODB simulation was run at 25 mph and 40 mph. The pre- and post-crash images and resulting C.G. and left rear accelerometer outputs are shown in Figure 30 and Figure 31. These runs verified that the higher speed impact yielded higher compartment accelerations than the lower speed impact.

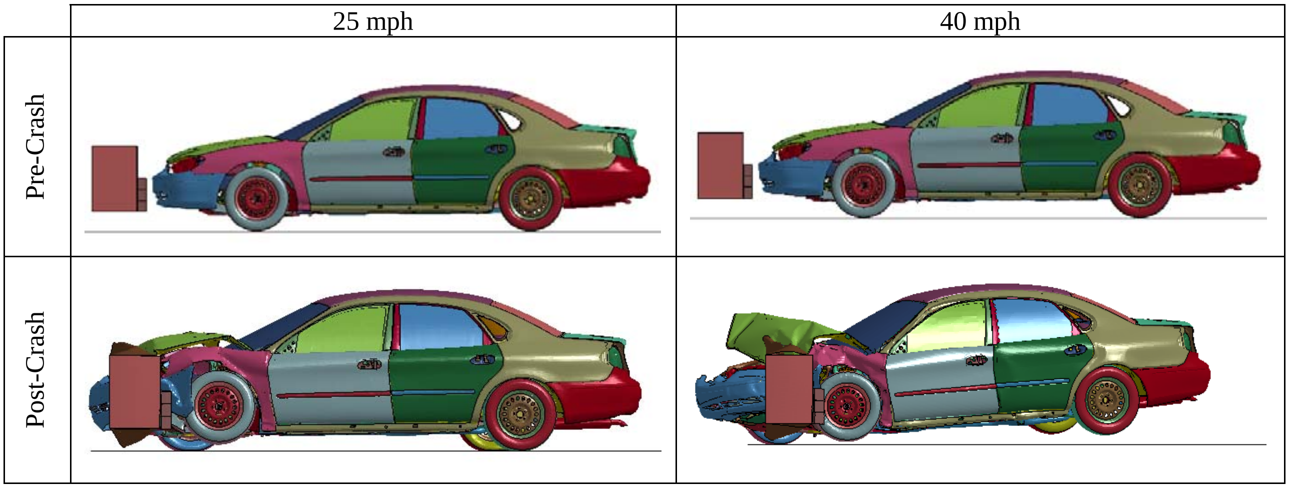

Figure 30 – Pre- and post-crash images of the Taurus for the IIHS ODB impact at 25 mph and 40 mph

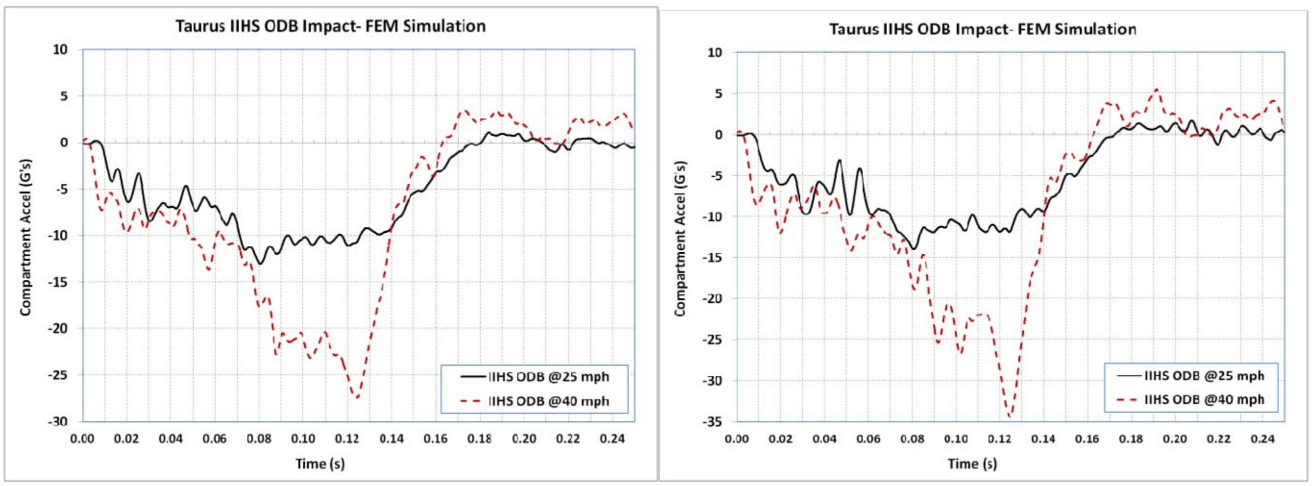

Figure 31 – Taurus CG (left) and left rear (right) accelerometer outputs for IIHS ODB verification simulations

Centerline Pole

The centerline pole simulation was run at 25 mph and 35 mph. The pre- and post-crash images and resulting compartment accelerations are shown in Figure 32 and Figure 33. These runs verified that the higher speed impact yielded a more severe crash pulse than the lower speed impact.

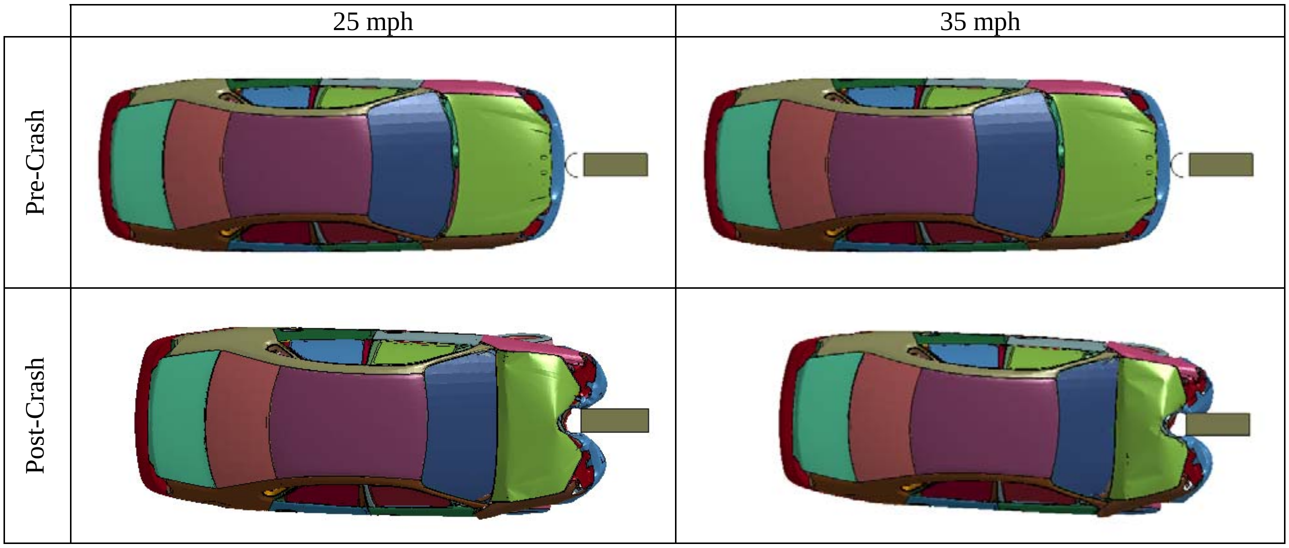

Figure 32 – Pre- and post-crash images of the Taurus for the centerline pole impact at 25 mph and 35 mph

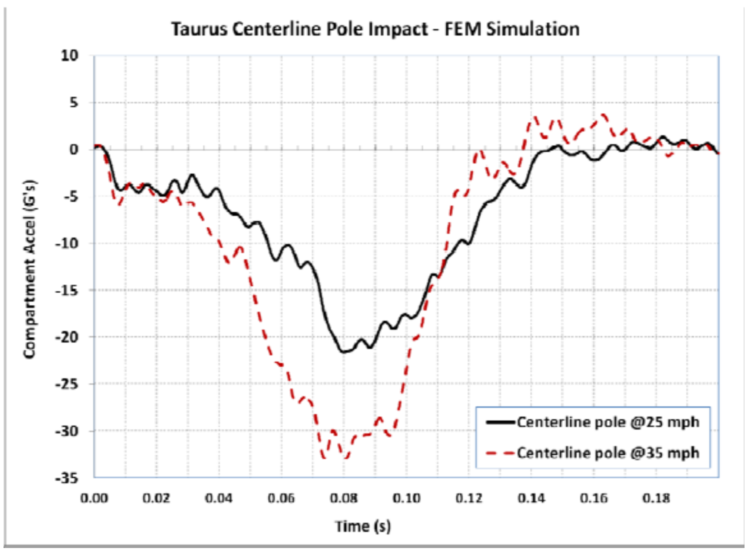

Figure 33 – Taurus compartment accelerations for centerline pole verification tests

SUMMARY AND CONCLUSIONS

A finite element model of the 2001 Ford Taurus passenger sedan was created using a reverse engineering process by the NCAC under contract to the FHWA. This vehicle was modeled to support NHTSA and FHWA research efforts.

The model was initially validated by comparison to images and data derived from the NHTSA NCAP tests, which involved frontal impact into a rigid wall at 35 mph. Comparisons of data from the tests and the model included:

- View of side deformations,
- Acceleration and velocity changes for the rear seat cross member,
- Accelerations of the top and bottom of the engine,
- Total forces over time, and
- Force displacement plots.

Vehicle kinematics and the accelerometer output data were compared and the simulation results showed overall good correlation with the physical test results.

Additional validation efforts were undertaken using data available from other crash tests, including full frontal wall, offset deformable barrier, moving deformable barrier, and offset rigid pole impacts. Simulation results compared well to data from these tests to determine the validity of the enhanced model. Robustness checks were also undertaken to demonstrate model performance in simulations of centerline pole impacts and full frontal collisions into a Chevrolet Silverado. The model provided viable representations in these large deformation crash events. The capabilities of the model were also checked by comparing the response trends for rigid wall, offset deformable barrier, and centerline pole impacts at varying speeds. The simulations executed without error in these runs and the results reflected the expected responses and consistency with varying parameters. This led to the conclusion that the model was robust across various impact scenarios.

This model development and validation process has proven the FE model of the Ford Taurus to be robust and applicable for the study of a variety of crash scenarios.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the Federal Highway Administration (FHWA) and National Highway Traffic Safety Administration (NHTSA) of the U.S. Department of Transportation for supporting these modeling and simulation efforts.

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